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JUNE, 1943
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With which is incorporated The Institution of Aeronautical Engineer

Edited for the Council by Capt. J. LAURENCE PRITCHARD, Hon. Fellow

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The ROYAL AERONAUTICAL SOCIETY, 4, Hamilton Place, W.1

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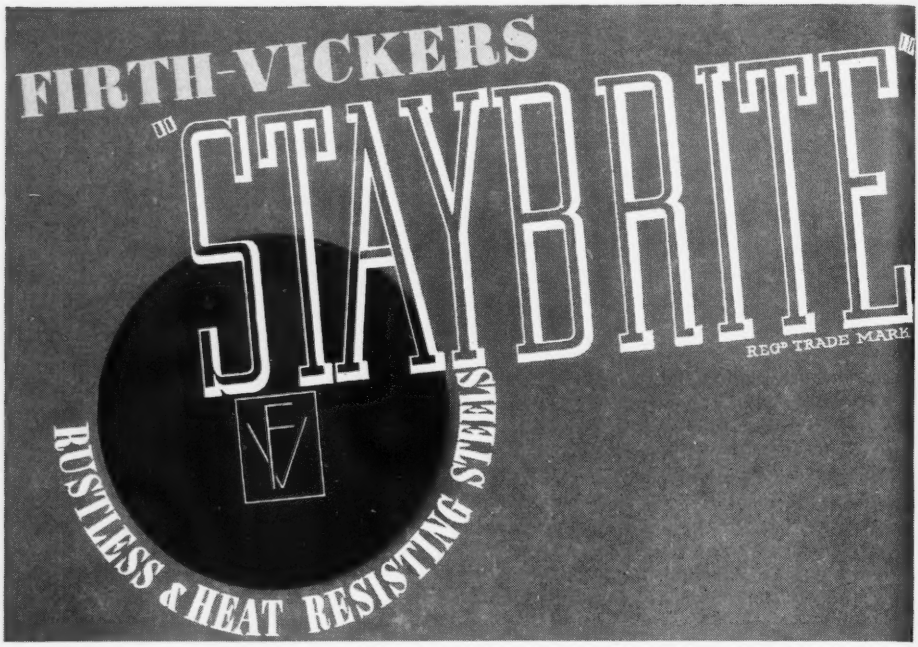
DETROIT



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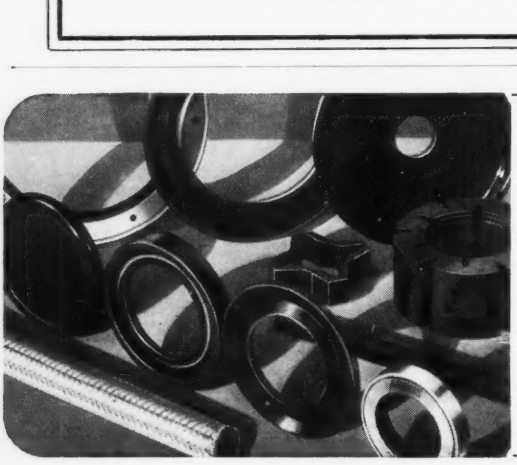

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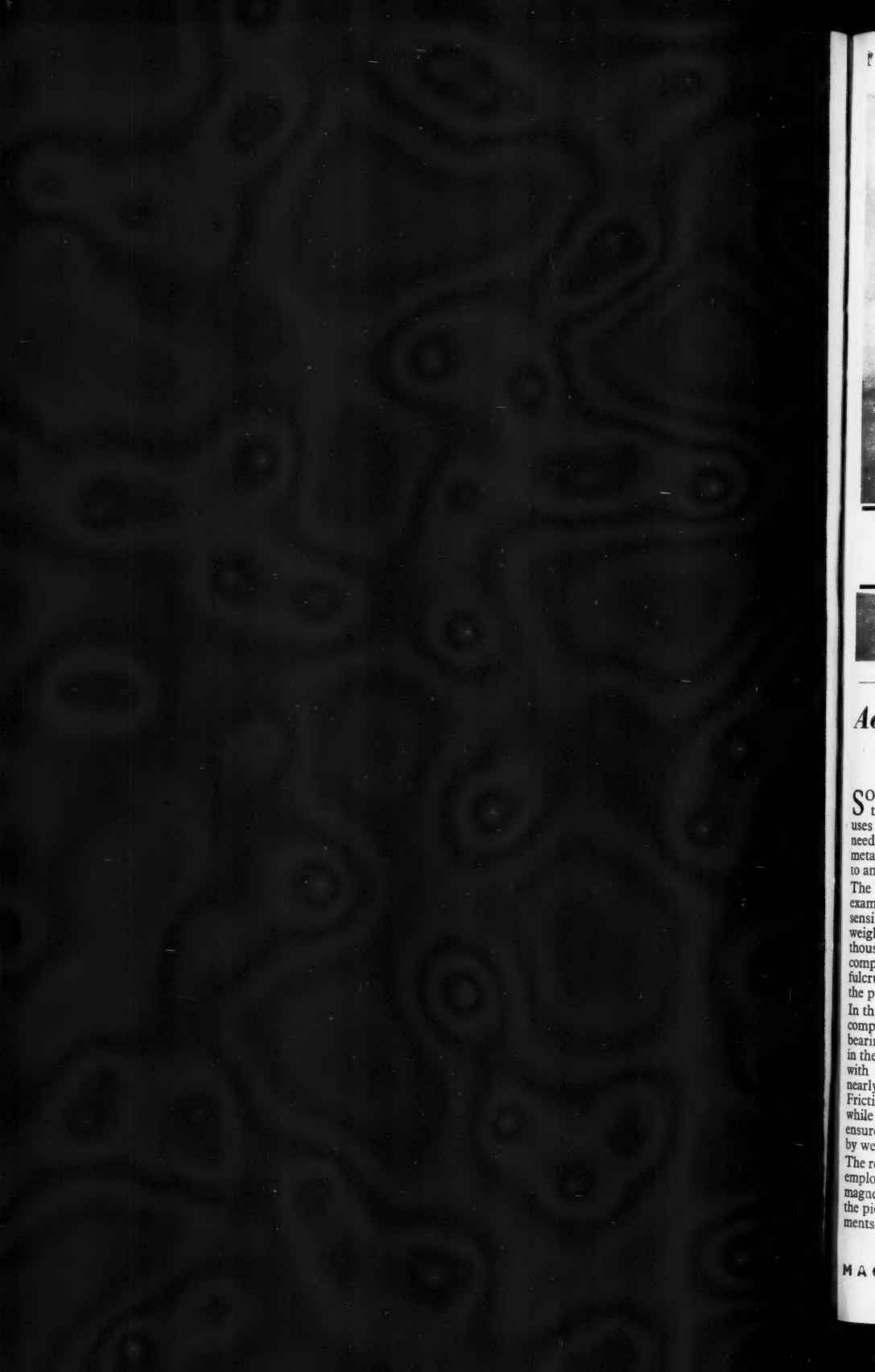

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"Aeroplane" photograph

Accuracy in the Balance

SOME of the most unexpected resources of the world are to-day being applied to new uses in the service of industry. To meet the need for exacting precision in the evolution of metallurgy, these resources have been tapped to an extent hitherto unknown.

The scientific balance illustrated is a fine example of this quest for accuracy. The sensitivity of this delicate instrument, which weighs to an accuracy of one hundred thousandth of a gram, depends on the almost complete absence of friction at the central fulcrum, and on the points of suspension of the pans at each end of the beam.

In this instance, a precious stone provides the complete answer to a difficult problem. The bearings of this balance are made from agate, in the form of a knife-edge resting on a plane, with the points of contact approaching as nearly as practicable to a theoretical line. Frictional forces are reduced to a minimum, while the unyielding hardness of this stone ensures that accuracy will not be diminished by wear.

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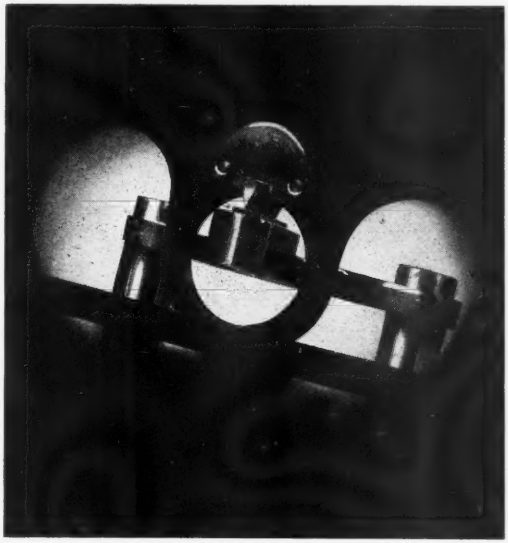

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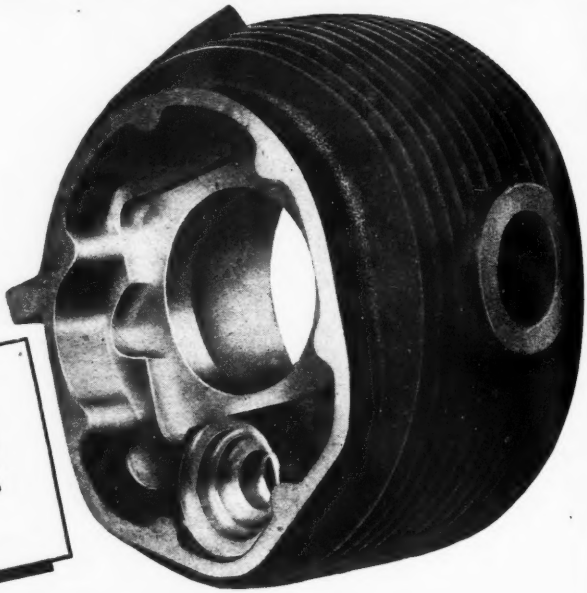

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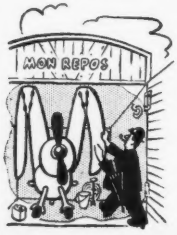

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From an article by Peter Masefield in "The Aeroplane" dated April 2, 1943

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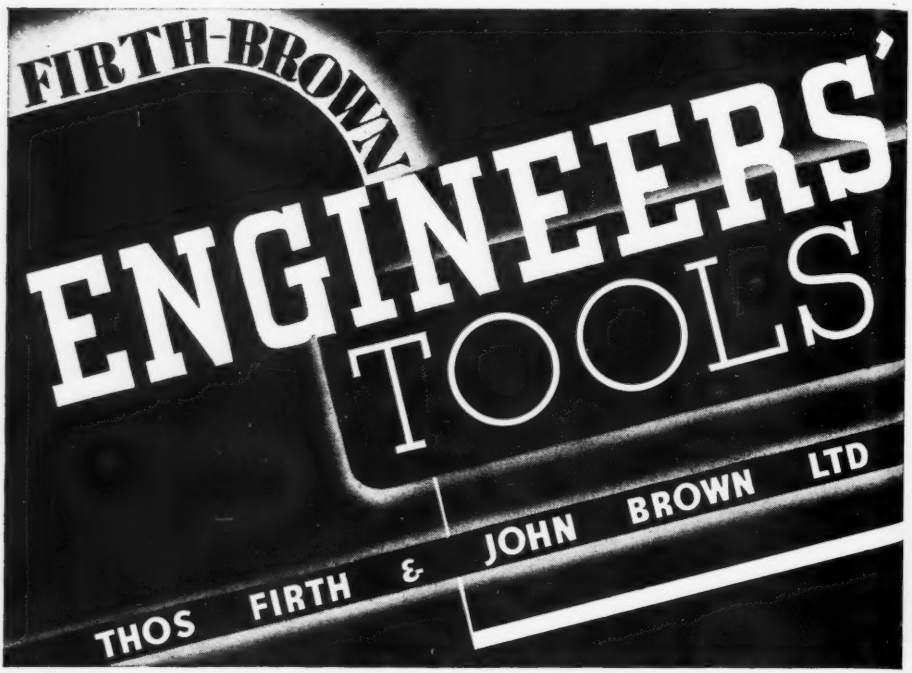

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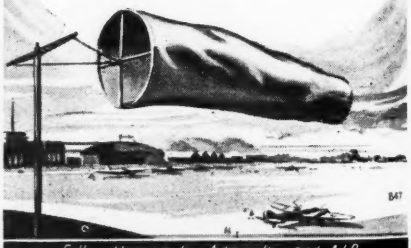

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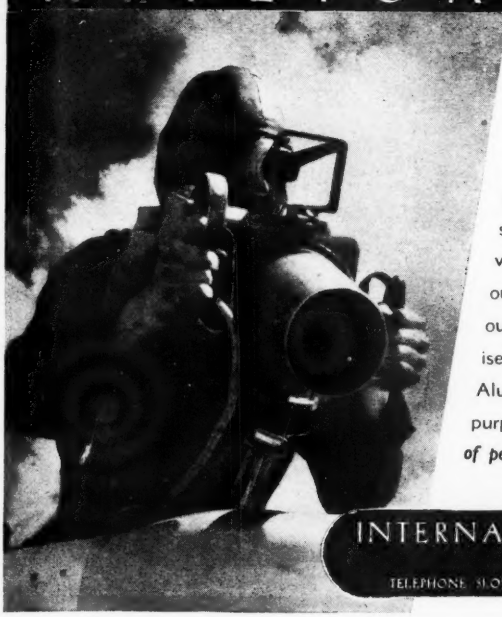

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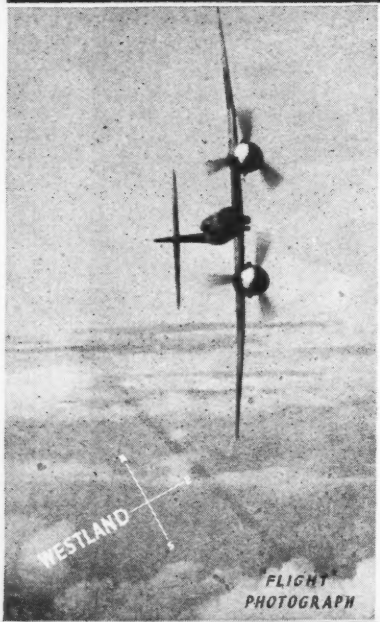

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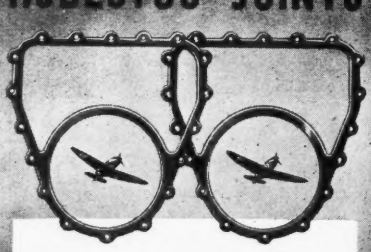

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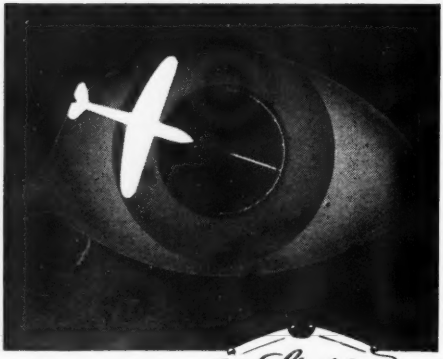

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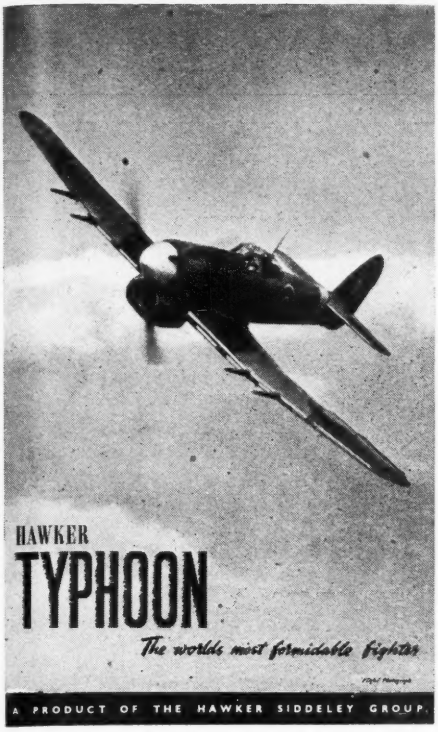

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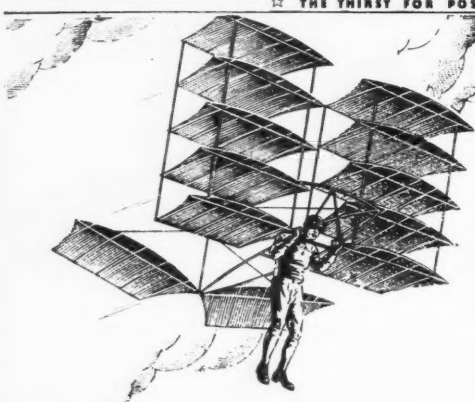
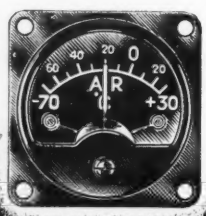


The Glider

Legend tells of many a brave man who devoted his lifetime in the effort to gain positive knowledge of controlled flight. Berblinger, 'the Flying Tailor of Ulm,' trusted his life to a flying suit of his own invention, escaping with no worse effects than a dip in the Danube. Octave Chanute, in the last century made over 1,000 glides in the apparatus illustrated here, which is said to have encouraged the Wright Brothers in their experiments. Positive knowledge of many aspects of flight is to-day provided to pilot and aircrew by Weston Instruments which guide and inform from take-off to landing.



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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY *was founded in* 1897 *in succession to the* ANNUAL REPORTS.

For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless such is definitely stated to be the case.

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A Radio Flight-Test Recorder.
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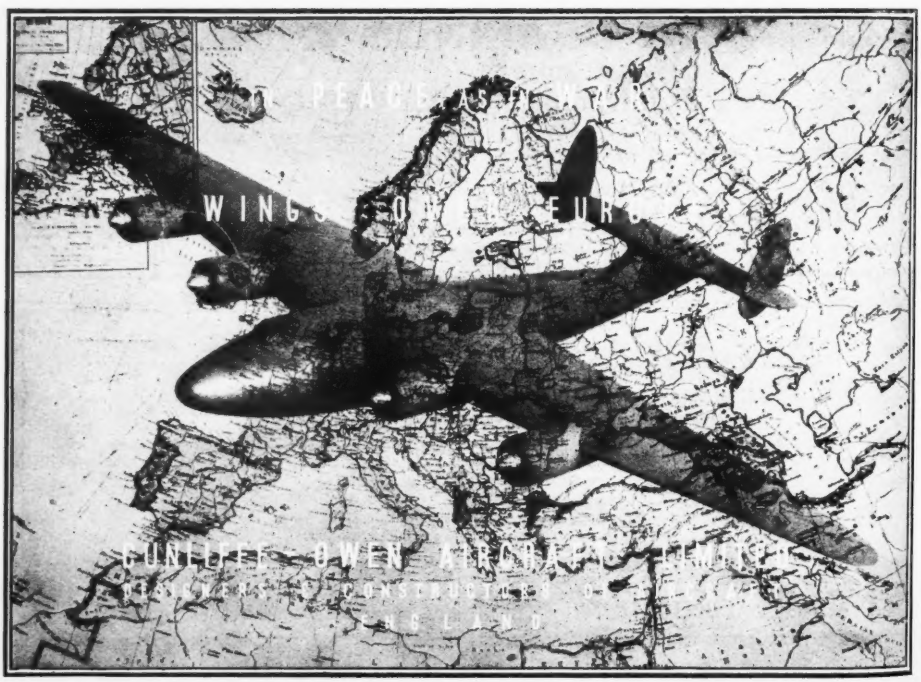

THE ROYAL AERONAUTICAL SOCIETY

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

MONTHLY NOTICES

JUNE, 1943.

Education and Training of Aeronautical Engineers.

A discussion will be held in the Lecture Hall of the Institution of Mechanical Engineers (by kind permission of their Council), Storey's Gate, Westminster, S.W.1, on Friday, June 25th, 1943, at 5.30 p.m. The discussion is intended to cover every side of aeronautical engineering training and will be opened by Sir Roy Fedden with a short outline of training of aeronautical engineers in America.

In view of the importance of providing for an adequate supply of trained engineers in industry, in research, and in the Royal Air Force, it is hoped that all those who have views on aeronautical education will come along and express them. The Society will welcome any written views.

Library Opening.

The Library will be open on Saturday afternoons from 2.30 p.m. to 5.30 p.m., on and after Saturday, June 19th, until further notice. A member of the Graduates' and Students' Committee will be in attendance on Saturday afternoons, and the Library will continue to be open as long as the attendance justifies it.

Changes of Address.

The attention of members is particularly called to the amount of work placed upon the heavily depleted staff by members who frequently change their addresses. It would considerably help the work of the office if members would give some permanent address to which Journals, etc., could be sent.

Owing to the extreme shortage of paper it will not be possible in the future to replace any Journals which have been lost in the post, due to such changes of address.

Graduates' and Students' Lectures.

The following lectures have been arranged as Joint Meetings with the Graduates' Section of the Institution of Automobile Engineers, and will be held in the Library of the Royal Aeronautical Society, 4, Hamilton Place, W.1 :—

Wednesday, 16th June, at 7.30 p.m.—" Applications of Photography to Engineering," by Dr. Baines, F.I.C., F.R.P.S., of Kodak Research Laboratory.

Wednesday, 14th July, at 7.30 p.m.—" Surface Finishing," by J. A. Oates, of " Aircraft Production."

Election of Members.

The following members were recently elected:—

Associate Fellows.—Edward Noel Brailsford (from Student), George Dobson (from Student), Harold Hay Hutchison, Alexander Jardine (from Graduate), Dennis Charles Jenkins (from Student), Thomas Bonar Lyon, Eric Beecroft Moss, Nyman Simmons, Charles James Walker (from Associate), Lawrence Roy Wilson (from Graduate), Charles George Alfred Woodford.

Associates.—Edward John Walter Ahier, David Drummond Anderson, Reginald Louis Attwood, Peter Bethell, Hubert Frank Chase, Leslie Peter Clarence Jack Dudley, Edgar Grocock, Herbert Norman Linforth, Kenneth McDowell, Donald Macfarlane, James Wesley McGinness (from Student), Sidney Joseph Paine, John Hall Sinclair, William Arthur Summers, Douglas Milton Wiggins.

Graduates.—Anthony Frank Carr, Walter Leonard Clarke (from Student), Edmund William Coates (from Student), Henry George Ewing, Howard Stanley Fowler, Robert John Garvey, Alfred C. Heggie, Stanley Steele Holman, Denis Keogh Kempston (from Student), Rhagavatula Venkata Sesha Chalapathi Rao, Bryan Oliver Shepherd, Ronald William Smith, David Herbert Whaley (from Student), James Benjamin Yates.

Students.—Alan Farrer Barker, Simon Brenner, John Frederick Cannell, Alan John Curzon, Cyril Lano Dodd, Frank Ferguson, Alan Victor Garrett, Ivor Edward Giles, Thomas Duncan Haywood, Douglas Gilbert Hitchcock, Samuel Stanley Laurie, William Maurice Locke, George Kenneth Mercer, Norman Nash, John Bernard Partridge, Reginald Charles Sanders, Reginald H. L. Shields, Alfred William John Smith, George Henry Watkin Thomas, Bernard Phillip Weaver, William Verley Williams.

Companions.—Edwin Gibson Pattison (from Student), Clive Thomas James Ware (from Student).

Additions to Library.

Pamphlets in italics with location reference following in brackets.
Books marked * or ** may not be taken out on loan.

A.a.297.—A Simple Study of Flight. (3rd Ed.) J. D. Haddon. Sir Isaac Pitman. 1943. 4/6.

*B.a.291.—*The Vega Ventura Bomber. Ministry of Aircraft Production. (Press Release, 24/4/43.)* (Y.3.iii.16.)

BB.a.13. Flight and Airframes for the Aircraft Fitter. D. O. Bishop and P. A. Bosanquet. Sir Isaac Pitman. 1943. 10/6.

C.f.25. *Life-Belts of the Air. Frank W. Lane. (Article in "Everybody's," 10/4/43.)* (Y.2.d.5.)

*D.a.C.19.—*Civil Aviation Statistics (Canada), Nov., 1942. Dominion Bureau of Statistics, Ottawa.* 1943. (File Case.)

*E.h.2.—*B.S. 1,100. Principles of Production Control: Office Aid to the Factory. British Standards Institution.* 1943. 6d. (PE.1.a.7.)

EE.c.69.—Aero-Engine Theory: A Fitter's Course. D. R. W. Archer and A. C. Ree. Sir Isaac Pitman. 1943. 10/6.

EE.c.70.—Aero Engines for Students. R. A. Beaumont. Allen and Unwin. 1943. 5/-.

*G.e.D.23.—Aero Research Technical Notes. Aero Research, Ltd. 1943.

*I.e.25.—*Four-Figure Mathematical Tables. Cargill G. Knott. W. and R. Chambers.* (PI.1/9.)

*Q.a.147.—Technical Library Catalogue. Rotol Airscrews, Ltd. 1943.

Q.b.70.—Report of Proceedings of 17th A.S.L.I.B. Conference, 1942. Association of Special Libraries and Information Bureaux. 1943.

TT.a.43.—The Flying Shadow. J. Llewelyn Rhys. Faber and Faber. 1943. 2/-.

*UU.c.—*National Advisory Committee for Aeronautics, U.S.A. Technical Memoranda*:—

No. 1,042. Theoretical Determination of Axial Fan Performance. E. Struve. (C.A.H.I. No. 295, 1937.)

No. 1,043. Experimental Investigation of a Model of a Two-Stage Turbo-Blower. S. Dovjik and W. Polikowsky. (C.A.H.I., No. 191, 1935.)

Special Notice: Annual Report, 1942.

The following matter was inadvertently omitted from the Annual Report for 1942, published on page 158 in the Journal for May, 1943:—

	£	s.	d.	£	s.	d.		£	s.	d.	£	s.	d.
Printing Costs ...	3234	4	9	(3350	12	3)	Sales	1590	14	5	(1460	3	0)
Postages... ...	320	12	4	(401	0	5)	Advertisements...	3230	15	5	(3344	18	3)
Other Charges ...	252	9	10	(168	19	0)							
Profit	1014	2	11	(878	9	7)							
	£4821	9	10	£4805	1	3		£4821	9	10	(£4805	1	3)

OFFICERS AND COMMITTEES OF THE SOCIETY.

The Council wish to place on record their appreciation of the work which has been carried out by the Honorary Officers of the Society during the year.

Captain A. G. Lamplugh, F.R.Ae.S., the Honorary Treasurer, has given invaluable advice and help on financial matters.

Mr. A. N. D. Smith, who completes his fifteenth year as Honorary Accountant, has continued to advise the Society particularly on the difficult problems of income tax which have arisen.

Mr. J. E. Hodgson, Honorary Librarian for so many years, has again during the year continued to advise the Society on all matters pertaining to the Library.

The Council wish particularly to place on record their appreciation of the work of the various Committees. Much of the work being carried out by certain of the Committees has involved many meetings during the year and the results which they have achieved will prove of very great value to the Society.

STAFF.

The Council wish to place on record their appreciation of the services of the staff, upon whom has fallen an added responsibility for the work of the Society during the war. The staff is less than one third of its pre-war size, but the work of the Society has been increasing. Much of that work is of a secret nature and it will not be possible to give details of the varied activities of the Society until the end of the war. The Society has a number of important Committees which are actively concerned with the war effort and the results of

their work have already proved of great value. The Society has also been able to arrange important meetings on war problems of which no account may yet be given, but which have proved invaluable in many directions and added greatly to the Society's prestige.

In addition to their normal duties the staff are responsible for Fire Guard and Civil Defence duties.

J. LAURENCE PRITCHARD, *Secretary & Editor.*

ON A NEW THEORY OF FREE TURBULENCE.*

H. REICHARDT.

(Zamm, Vol. 21, No. 5, October, 1941.)

Translated by M. FLINT.

Measurements of momentum in regions of turbulent mixing show that an analogy exists between the processes of turbulent and molecular balance which enables a rational application of the differential equation of thermal conduction to the propagation of turbulent momentum to be made. This fact forms the basis of a new phenomenological theory of free turbulent flows.

1. EFFICIENCY AND LIMITATIONS OF THE HITHERTO EXISTING THEORY OF THE MIXING PATH.

Whilst the molecular theory can be developed from definite postulates, because the elements of the relevant statistics, viz., the molecules, are previously given, the theory of turbulence is in the difficult position of possessing no sound basis upon which any statistics can be formed. This is due to the fact that the elementary constituents of turbulence, namely, the vortex whirls, are extremely variable structures, which affect each other in a manner very difficult to recognise. The results or the methods of molecular physics cannot therefore be applied directly to the mechanics of turbulence.

In spite of considerable differences, however, the molecular and turbulent processes have certain essential features in common. For example, there is a similarity in the transmission of shear. In both cases the shearing stress is brought about by the fact that elementary parts with a certain value of momentum of the principal velocity, as a result of a transverse motion about a " free length of path," reach a new environment with another principal velocity and there, through impact or mixing, impart their excess momentum to the neighbouring parts or slow them down through their smaller momentum.

It is therefore natural to apply the physical interpretation of the molecular concept of the free length of path to the motion of turbulent interchange and employ this quantity for the representation of the turbulent apparent friction. A concept corresponding to the free length of path, viz., the so-called Prandtl " mixing length," has indeed been evolved from such considerations[1] for turbulence. This Prandtl mixing length rendered it possible for the first time to deal mathematically with turbulent flows.

On the basis of the notion that an eddy whirl travels a certain path l' without mixing with its surrounding medium, Prandtl obtains for the variable velocities u' (in the direction of the principal flow) and v' (in the transverse direction) the expressions

$$u' \sim l'_u \frac{d\bar{u}}{dy}, \quad v' \sim l'_v \frac{d\bar{u}}{dy}$$

and thus for the turbulent apparent friction $\tau = \rho \overline{u'v'}$ the relation

$$\tau = \rho l^2 \left|\frac{d\bar{u}}{dy}\right| \frac{d\bar{u}}{dy} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

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* Reprinted by permission of the Ministry of Aircraft Production (R.T.P.).

[1] L. Prandtl. Bericht über Untersuchungen zur ausgebildeten Turbulenz. Z.A.M.M., Vol. 5, 1925, p. 136.

Here $\bar{u}$ is the mean velocity in the direction of the principal flow x, y the transverse direction in which the interchange takes place, ρ the density of the medium and l the quantity defining the " mixing path " derived from the mean value of l'_u and l'_v.

To enable the mean velocity of a turbulent flow to be calculated, suitable data for the quantity l were still needed. Here of necessity resort had to be made to the empirical facts which provided the basis for the development of useful theorems.

Since its first formulation in 1925 the theory of the mixing path has been applied in many cases, as manifested abundantly in literature. These investigations are concerned in part with the flows in the neighbourhood of walls, but chiefly with the processes of turbulent propagation without obstruction due to walls. These processes of the so-called " free turbulence," owing to their relative simplicity, are also comparatively easy to deal with.

The results hitherto obtained by the application of the mixing path theory may be briefly summarised as follows: In many cases the mean motion of the flow has been calculated approximately. The logarithmic velocity profile which appears in friction layers has been explained. In the matter of free turbulence the main features of the observed rules governing the propagation of the mixing regions in the direction of the principal flow have been correctly interpreted.

The results obtained hitherto, however, have not been so rigid as to admit of no other explanation. It cannot therefore be actually claimed that the concept of the mixing path has been confirmed by experiment and that it has been the means of acquiring any essential insight into the structure of turbulence. The following objections present themselves in this connection.

The investigations are concerned exclusively with the calculation of the *mean* velocities and their comparison with the measured mean values. These mean value investigations alone, however, are not sufficient for the determination of a quantity which is to be characteristic for the structure of turbulence. An explanation of the notion of the mixing path will therefore depend essentially on investigations of *fluctuations*, the purpose of such investigations being to determine the relation between the fluctuation quantities and the mean values.

But the mean value investigations carried out up to the present have also been hampered from the outset by a fundamental difficulty. The original theorem[1] leads to velocity profiles which, compared with the measured profiles are much too sharply pointed at their maxima (in particular the velocity gradient and the second derivative show that the run of the calculated profiles may not be correct). For a physically satisfactory representation of turbulent profiles therefore, Prandtl in his first publication[2] gave a more complicated expression of the form

$$\tau = \rho l^2 \frac{d\bar{u}}{dy} \left\{ \left(\frac{d\bar{u}}{dy} \right)^2 + l_1^2 \left(\frac{d^2\bar{u}}{dy^2} \right)^2 \right\}^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (2)$$

In addition to the actual mixing length l a second mixing length l_1 is defined by this expression. As the expanded theorem contains two freely disposable quantities, the theory can be better adapted to experiment. It has been possible in fact, in individual cases, though a great deal of mathematical computation was involved, to calculate with theorem,[2] profiles conforming faithfully to the true profiles.

Considered physically, the method of working with two free quantities adapted to the momentary requirements, however, is not by any means satisfactory. If it is already far from easy clearly to define the length l, the length l_1 introduced from further qualitative considerations would appear to be still more difficult to interpret. The question therefore arises as to whether any advance at all can be

[2] cf. Footnote 1.

made from the physical point of view along the lines of the theory hitherto followed.

2. The Suitability of the Inductive Method.

It seems to the present author that an essential cause of the present position of the theory lies in an over-estimation of the deductive method of consideration adopted in turbulence research. The mathematical hydrodynamician is accustomed to accept the equations of motion as found on a physically sound basis. This is certainly justified to a large extent in hydrodynamics. In many cases the theory is definitely correct, when the problem can be dealt with mathematically. In the case of difficult problems which can only be solved approximately, experimental data are very often needed. But then these data are in fact incorporated organically in a theory which in itself is reliable.

The circumstances in turbulence research, on the other hand, are quite different. Here we have practically no theoretical bases whatever to go upon. These bases have indeed first to be created. Resort must therefore be made essentially to the evidence of experiment, and even here there is a tendency to develop the theory by deduction on the bases of general assumptions, which is tantamount to putting hypothetical theorems to the test. This work of adapting a theorem to the experimental facts, however, is rendered difficult because of the whole mass of calculations, mostly highly complicated, which come between the theorem and the experiment and, with every variation of the postulates, has to be worked out afresh.

For researches on turbulence based on experiment, on the contrary, it would appear more suitable to adopt the inductive method by establishing a direct foundation of the theory on the experimental results. When the actual phenomena have been mathematically represented, the correct "theorem" will certainly be obtained by reversing the mathematical procedure hitherto followed.

Naturally the inductive method also has its difficulties because the "correct" curves must be made to lie through the scattered measurement points. Further, both the measurement errors and the influences of superposed effects of a higher order (which in a field of research still little explored are at first of no interest) must be correctly assessed. The solution of this problem of discovering the essential governing laws from the most widely differing measurement results within the limits of an inevitable uncertainty, however is relatively easy, when once through exhaustive observation of the phenomena a practicable hypothesis has been evolved.

Thus even with purely phenomenological procedure, speculative considerations cannot be dispensed with altogether. Compared with the deductive methods, however, there is this fundamental difference, that the idealising assumptions are directly related to the measurement results. A direct check on hypotheses is thereby rendered possible.

3. On the Possibility of a Comparison Between the Processes of Molecular and Turbulent Balance.

In flows of free turbulence no great difficulty is entailed in forming a general hypothesis. As it is a matter here of statistical balance processes, a comparison of the turbulent processes with the molecular phenomena of diffusion and thermal conduction naturally suggests itself. Even though in their details the molecular and the molar processes take place quite differently, it is on the other hand highly probable that with the turbulent processes also in the end effect purely statistical distributions will be obtained. In fact the measured velocity distributions in free jets and in dead-water regions in many cases exhibit a strong similarity with the Gauss error curve. The error curve represents the run of the profiles

in particular in the neighbourhood of the maximum (which does not work out correctly with theorem (1) very satisfactorily.[3]

The obvious inference therefore is, that differences of momentum[4] in a flow of free turbulence are balanced in a manner similar to differences of concentration or differences of heat or temperature. For example the momentum curves, measured ten years ago by H. Muttray,[5] which exhibit the gradual fading-out of a momentum trough behind a body of resistance and the known fading-down curves of the thermal conduction theory are so alike as to be hardly distinguishable. (It is necessary merely to exchange the distance x from the position of the disturbance appropriately with the time parameter of the temperature curves.)

The hypothesis, that the distribution of turbulent momentum of the principal motion is capable of being represented by a partial differential equation of the type of the equation of thermal conductivity (the place parameter appearing in place of the time parameter) will thus readily present itself to an unprejudiced observer of the Muttray measurement results. We therefore put

$$\frac{\partial \bar{u}^2}{\partial x} = \Lambda \frac{\partial^2 \bar{u}^2}{\partial y^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The reason why the equation of thermal conduction has not yet been applied to the processes of free turbulence (the present author at any rate is unaware of any such attempt having been made) must be due to the existence of a certain prejudice against a solution of this kind. In fact the question of analogy also gives rise to a fundamental objection, namely, that a quantity corresponding to that of the thermal conductivity, does not exist in the momentum case. The physical significance of the quantity of equation (3) therefore (at first sight at least) is not clearly seen.

This objection however is not decisive, because every new theory at first brings in new unknowns. There must therefore have been another reason against the consideration of a molecular analogy. Apparently this lay in the available results obtained from previous investigations of the so-called free jet boundary (where a free jet at constant velocity comes into contact with fluid at rest), which were incompatible with such a manner of approach to the problem.

The plane contact of two jets with different velocity corresponds in the thermal case to the plane contact of two bodies with different temperature. The theory of thermal conduction as we know leads to temperature distributions in the transitional region, which are represented by error integral curves. When the bodies have the same conductivity, the plane contact always has the mean temperature, and the two branches of the error integral curve lie (with changed sign) "symmetrically" with respect to the boundary surface. Thus, if the analogy between the processes of the molecular and the turbulent balance is really suitable, the momentum curves in the region of mixing of two jets must

[3] The error curve naturally can no longer hold on the outermost boundaries, because the potential motion of the outer space sets a limit on the turbulent propagation.

The velocity distributions measured in the two-dimensional free jet by Förthmann were recently represented by Okaya and Hasegawa by the equation

$$u = u_{\max} e^{-\frac{1}{2}\lambda^2}\left(1 - \frac{\lambda^4}{k}\right),$$

where $\lambda = y/x$ and $k = \text{const}$. The authors discuss the compatibility of this velocity formula with the mixing path theorem (2). (Proc. Physico. Math. Soc. Japan, No. 3, Vol. 22, 1940.)

[4] The velocity as such is not physically effective, but the momentum ρu^2. When ρu^2 is represented by an error curve, the distribution of u is also an exponential function. In wake regions the loss of momentum is approximately $-2Uu_1$ (U = constant principal velocity, u_1 = velocity loss). Here therefore (with moderately large values of u_1) loss of momentum and loss of velocity are proportional to each other.

[5] H. Muttray. Die experimentallen Tatsachen des Widerstandes ohne Auftrieb. Hdbk. d. Exper. Phys. von Wien-Harms. IV. 2, p. 325, 1932.

be error integral curves, which likewise (in the given sense) lie symmetrically with respect to the boundary surface.

A lack of symmetry might naturally be explained by the assumption of different "momentum conductivity" on the two sides of the boundary. Such an expedient however is not permissible, since our considerations of analogy, which is intended only to interpret the essential nature of the process of turbulent balance, can only have physical meaning and be pursued by adopting the assumption that the capacity of propagation of momentum is independent of the value of the momentum itself and (at any rate as a first approximation) of y. That the turbulent processes as a second approximation are very probably quite different and considerably more complicated than the corresponding molecular processes, hence that a comparison in the second approximation would be highly problematic, need not be discussed more closely here.

The investigations at the free jet boundary hitherto carried out, refer to the most easily realisable and practically important limit case, where the u-velocity vanishes on one side, thus where a jet of constant velocity comes into contact with fluid at rest. Here, therefore, at the boundary surface we should expect half the momentum of the maximum velocity, and the distributions of momentum on either side of the boundary would have to correspond exactly one with the other. In reality, however, as yet only distinctly asymmetrical distributions of the total pressure (which in practice corresponds to the momentum), have been measured.[6] The total pressure of the boundary surface was always found to be smaller than half the maximum pressure, and the curves of the measured distributions run flatter on the side of the fluid at rest and much more steeply into the jet.

The pronounced asymmetry of the measured momentum curves may also appear plausible, because fresh fluid is continually being sucked in from the region of rest, but not, on the contrary, from the other side. Thus different hydrodynamical conditions undoubtedly exist on the two other sides of the boundary. Added to this is the fact, that the established asymmetry of the total pressure distribution could be quite well explained by the mixing path theorem (1). It can therefore be very readily understood why a comparison between the processes of turbulent and molecular balance has not been attempted, more particularly since the study of the boundary of the jet (whose behaviour was of considerable interest in connection with the design of wind tunnels), belonged to the earliest investigations on the subject of free turbulence.

These arguments against the application of a consideration of the molecular analogy, however, are only apparently inconsistent. The quantity of the fluid sucked in on one side from the fluid at rest does indeed play an essential part, but the transverse pulse of the unilateral inflow is nevertheless quite insignificant. From the point of view of the balance of momentum (and this is the only point concerned in the consideration of the analogy) the asymmetry referred to is therefore negligibly small.

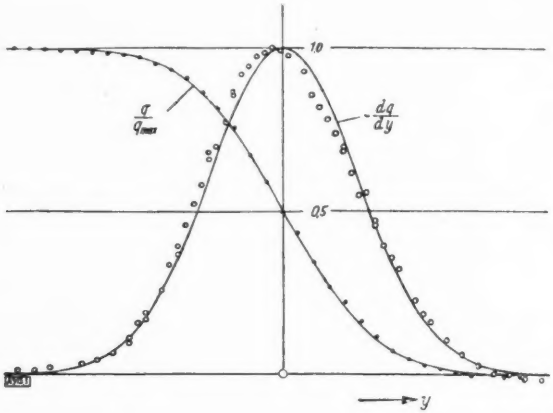
But do not the available measurements nevertheless speak against an application of the molecular analogy? This also is only an illusion. The measurements were carried out on jet boundaries which were not by any means truly two-dimensional. The early Göttingen measurements refer to the circular free jet, and the original rectangular jets of Cordes and v. Bohl at a certain distance from the nozzle also probably ceased to be absolutely plane.[7] In the case of the circular free jet it is fairly obvious that the run of the momentum curve outwards is flatter and inwards into the jet is steeper. (The corresponding thermal conduction problem (heated cylinder in a colder surrounding medium) is also asymmetrical).

[6] cf. Ergeb. d. Aerodyn. Vers. Göttingen, 2nd Ed., 1923, p. 69; further, G. Cordes, Ing. Arch., Vol. 8, 1937, p. 245; v. Bohl, Ing-Arch., Vol. 11, 1940, p. 295. (Cordes' measurement points deviate only slightly from the error integral curve.)

[7] W. Tollmien. Berechnung turbulenter Ausbreitungsvorgänge. Z.A.M.M., Vol. 6, 1926, p. 468.

The decision of the question whether an application of the molecular analogy to the processes of free turbulence is fundamentally possible or not, thus depends on measurements of total pressure on a true two-dimensional jet boundary. The present author has therefore been engaged in such investigations. By suitably guiding the jet it was contrived that practically two-dimensional conditions were still presented even at a relatively great distance from the nozzle.

The investigations carried out under these conditions now show that the distributions of momentum are, as a first approximation, actually symmetrical and can be represented surprisingly well by error integral curves. This fact was proved by many careful measurements at the most widely varying distances from the nozzle.



Total pressure distribution in the mixing zone of the two-dimensional jet boundary.

The figure shows the results of one such series of measurements. The black dots indicate the total pressure values q determined at the individual transverse distances y for a specified x-distance from the nozzle (these values are referred to the maximum total pressure q_{max} of the nozzle flow). The full-line is the error integral curve which runs to the boundary $y=0$ through the point $q/q_{max}=0.5$, which with its two branches (in the given sense) lies exactly symmetrical with respect to the boundary surface. The measurement points lie either on or in the immediate neighbourhood of the error integral curve. On close examination it is seen that a slight asymmetry undoubtedly exists. This, however, is so trivial that it only appears distinctly with a very high degree of measurement accuracy (which was achieved by obtaining mean values over relatively long periods of time).

Owing to the importance of this question the differential quotient of the impulse for a distance x was determined from the pressure difference of two small closely neighbouring pitot tubes. The results of these differentiation measurements are shown by the light circles (the individual values referring again to the highest value). With exactly symmetrical conditions the measurement points would lie on the error curve drawn in the figure, which is obtained from the differentiation of the full-line error integral curve. Actually the measurement points are displaced slightly to the left. The slope of the total pressure curve is thus actually slightly flatter on the outer side than on the jet side.

The departures from the symmetry, however, are so small that for a theory of the first approximation they may safely be neglected.[8] The essential argument against the application of the molecular analogy to free turbulence is thus removed.

The intuitive application of the theory of thermal conduction to the processes of turbulent propagation also obtains its particular justification owing to the fact that the statistical functions of the error curve and of the error integral curve represent the measured distributions of momentum considerably better than the functions obtained with the mixing path theorem (1). Besides this, the mathematical work is incomparably simpler than that entailed by the mixing path theory.[9]

4. Development of a Phenomenological Theory of Free Turbulence on the Basis of the Molecular Analogy.

A brief résumé of our theory is given below.

The distributions of momentum in two-dimensional free jets (slot jets) and in two-dimensional wake regions in accordance with the available measurements can be represented with good approximation by the equation

$$\bar{u}^2 = c_1 + \left(\frac{c_2}{b}\right) e^{-(y/b)^2} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

(where the length b is a measure, variable with x, for the width of the mixing zone and c_1 and c_2 are constants).

This equation is a solution of the differential equation (3), if, for the " transmission quantity " Λ, we put

$$\Lambda = \left(\frac{b}{2}\right)\left(\frac{db}{dx}\right) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

As the distribution of momentum at the boundary of a two-dimensional jet, which borders on a fluid at rest, can be represented approximately by an error integral curve, we may also put quite generally for the case of the two-dimensional contact of two parallel jets :—

$$\bar{u}^2 = c_1 + \left(\frac{c_2}{b}\right) \int_0^y e^{-(y/b)^2}\, dy \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This equation also is a solution of (3) if, for the transmission quantity we again introduce relation (5).

The distribution of momentum at a relatively large distance behind a plane grid may again be represented in good agreement with available measurements[10] by the equation (7).

$$\bar{u}^2 = c_1 + c_2 e^{-f(x)} \sin(2\pi y/\beta) \quad . \quad . \quad . \quad . \quad (7)$$

[8] It is unreasonable to demand too great a degree of accuracy, because with intense turbulence (particularly in the boundry regions) systematic measurement errors are bound to appear. Besides this, the difference between the measured total pressure $p + \frac{\rho \bar{u}^2}{2}$ and the momentum ρu^2 is of the order of value of the deviations of the measurement points from the error curve or the error integral curve.

It might moreover also be conceivable that $p + \rho u^2$ and not ρu^2 is statistically distributed (equation (10) would then be modified accordingly). Such refinements, which in themselves are of fundamental significance, cannot, however, be assessed at the moment, since a sufficiently exact method for the determination of the static pressure is still lacking.

[9] A detailed exposition of the laws governing free turbulence on the basis of the theory developed here will be published shortly as a VDI-Forschungsheft. In this paper also the suitability of the statistical functions for the representation of the variation of momentum (impulse) is proved in detail on the strength of a large number of measurements.

[10] R. Gran Olsson. Geschwindigkeits-und Temperaturverteilung hinter einem Gitter bei turbulenter Strömung. Z.A.M.M., Vol. 16, 1936, p. 257.

(Here β is the grid spacing. The exponent $f(x)$ according to the measurements available appears to be proportional to x.)

Equation (7) is likewise a solution of (3), if for Λ we put:—

$$\Lambda = \left(\frac{\beta^2}{4\pi^2}\right)\left(\frac{df}{dx}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

We have thus determined the transmission quantity for the two cases of the variable and the constant mixing width. No fundamental physical interpretation, however, is achieved by this purely formal determination of Λ. (The physical significance of Λ will in fact not be clearly recognised until it has become possible to represent the processes of free turbulence by statistics of the vortex whorls.)

Having established that equation (3) very approximately represents the law governing the transmission of momentum for the known region of free turbulence, we have now to seek the "theorem" which is necessary if the differential equation (3) is to follow from the equation of motion.

The equation of motion of the two-dimensional problem expressed in the momentum form neglecting viscosity forces is

$$\left(\frac{\partial}{\partial x}\right)\left(\frac{p}{\rho} + \bar{u}^2\right) + \frac{\partial \overline{uv}}{\partial y} = 0 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If further, as a first approximation, we neglect the pressure differences (which in the processes which led to equation (3) is certainly permissible), we see that equation (3) is obtained from the equation of momentum only when for $\overline{uv}$ the relation

$$\overline{uv} = -\Lambda \frac{\partial \bar{u}^2}{\partial y} . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

holds.

This relation concerning the wandering away of the u-momentum into the v-direction is thus the result of our inductively developed theory of free turbulent flows.

The "law of transmission of momentum" represented by equation (10) is interpreted as follows: *The flux of the u-momentum, which wanders away into the transverse direction y, is proportional to the u-momentum gradient in this direction.*

The transmission of momentum takes place in planes, which are described by the u-direction and the gradient of the u-momentum. The law of transmission expressed in vector form is therefore

$$j\overline{uv} = \Lambda\,[i\,[i \nabla \bar{u}^2]] \quad . \quad . \quad . \quad . \quad . \quad (10a)$$

where i and j denote the unit vectors of the longitudinal and transverse direction respectively (the transverse direction j is defined by (10*a*).

The relation (10*a*) is independent of the reference system. This is because i is not an arbitrary vector, but describes the actual direction of motion of the fluid before its entry into the region of the turbulent mixing.

The result of our investigation is noteworthy in that, contrary to expectation, we have found no expression for the apparent turbulent friction. Namely, equation (10) shows merely how the *resultant* momentum $\rho\overline{uv} = \rho\overline{u'v'} + \rho\bar{u}\bar{v}$ is propagated. Nothing is asserted as to the behaviour of $\rho\overline{u'v'}$ alone, and for the mechanism of free turbulence only the sum of the steady and of the unsteady portion of the transverse transport is available without any recognisable distinction between these terms.[11]

[11] From the statistical standpoint the factors $\overline{u'v'}$ and $\overline{uv}$ are obviously equivalent and the characteristics of these terms are solely of a hydrodynamical nature. The equality of $\overline{uv}$ and $\overline{u'v'}$ seems plausible in as much as the steady v-motion also is a direct result of the action of the turbulence on the fluid. (Without the turbulence, with the postulated absence of friction, there would be no v-component and only the u-velocity would vary discontinuously at the jet boundaries).

Naturally equation (10) may be resolved with respect to $\overline{u'v'}$. The question still exists, however, whether such an equation for $\overline{u'v'}$ does not represent a special case of a universal shear formula which holds for free turbulence.

A possible form for a general shear expression would be, for example,

$$\tau/\rho = -K\left(\frac{B}{\overline{uv}} + \frac{\partial \bar{u}^2}{\partial y}\right) 0 < k < 1 \quad . \quad . \quad . \quad . \quad (11)$$

The factor K with free turbulence 1 (when (11) becomes identical with (10)) and with non-turbulence or turbulence without apparent friction is $K=0$.

The appearance of a turbulent shearing stress, as known, is associated with the existence of a correlation between the longitudinal and the transverse motions. Now the factor k of this correlation vanishes not only for certain turbulent flows (for example for fading out, isotropic turbulence), but also for periodic vortex motions (Kármán-vortex).[12] As free turbulence develops from roughly periodic disturbances, the obvious course is to seek to formulate the factor K as a function of the correlation coefficient k, for example $K=$ factor k.

5. The Extension of the Mixing Zones in the x-Direction.

In the foregoing considerations the question of the dependence of the variation of the width of the mixing zone on the co-ordinate x was not considered and has therefore still to be determined. In the considerations up to the present operating with the concept of the mixing path, only such cases were considered, in which the velocity profiles were affinely related at the different distances x. By putting the expression for the apparent shear into the hydrodynamical differential equations we automatically obtain the powers of x, according to which the width of the mixing region increases and the velocity decreases (in so far as the latter does not remain constant, as at the boundary of the jet).

Since in the new theory the momentum profile is available already from the outset, in that here also the different momentum profiles of one and the same flow are in affine relation, it is sufficient to formulate this affinity, as in equations (4) and (6), and note the powers by which equations (3), (5) and (10) can be satisfied. Here it is necessary merely to assume further, that the distributions of the flows, including the fluctuations in the individual cross-sections are similar to each other, that, for example the velocity fluctuations at corresponding transverse distances are definite fractions of the maximum velocity difference $u_{1\,\max}$ and that $\overline{uv}$ may be put proportional to $\bar{u}$, $\bar{v}$. From (10), using (5) for Λ, it is then found that

$$\left(\frac{db}{dx}\right)\frac{\partial\,(\bar{u}^2/u_{1\,\max}^2)}{\partial\,(y/b)} = f\,(y/b) \quad . \quad . \quad . \quad . \quad (12)$$

depends only on y/b.

For the velocity we put

$$u = U + u_1$$

where U is a constant velocity and differences in velocity relative to U are expressed by u_1.

With the two-dimensional wake, for small u_1/U we may write approximately $\bar{u}^2 = -2Uu_1$.

From (12) therefore (since for reasons of similitude $u_1/u_{1\,\max}$ depends only on y/b) it follows that

$$\left(\frac{U}{u_{1\,\max}}\right)\left(\frac{db}{dx}\right) = \text{const.} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

From this it follows further (since here in accordance with the theorem of momentum $u_{1\,\max}\,b = \text{const.}$) that

$$b \sim \sqrt{x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

[12] W. Tollmein. Uber die Korrelation der Geschwindigkeitskomponenten von periodisch schwankenden Wirbelverteilungen. Z.A.M.M., Vol. 15, 1935, p. 96.

Such a distribution of the mixing width has been known for two-dimensional wakes since the time of the measurements by Schlichting.[13]

In the case of the two-dimensional free jet in surrounding fluid at rest, u and u_1 are identical. With the two-dimensional contact of two jets $u_{1\,\max}$ is a constant. In both cases for reasons of similitude $u^2/u_1{}^2{}_{\max}$ depends only on y/b. Hence from (12) it follows that $db/dx = \text{const.}$ and

$$b \sim x \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

We have thus correctly reproduced the linear propagation of the mixing width known for jets.

6. Summary.

1. It is established that the distributions of momentum in motions of turbulent propagation are described with good approximation by the statistic functions of the error curve and the error integral curve. The processes of turbulent and molecular balance may therefore be compared in a certain manner one with the other, so that the rational application of the differential equation of thermal conductivity to the propagation of momentum in free turbulent flows is possible.

2. From this differential equation of momentum and the hydrodynamical equation of motion it follows that the total flux of the u-momentum (brought about partly by the fluctuation motions, partly by the steady transverse motion) wandering into the transverse direction is proportional to the u-momentum gradient in this direction. As the factor of proportionality, the "transmission quantity" Λ of the momentum appears, which is determined as a function of the mixing width by the theory itself.

3. By means of the formula for the transmission quantity the known laws governing the extension of the mixing regions can be correctly represented on the basis of considerations of similitude.

[13] H. Schlichting. Uber das ebene Windschattenproblem Ing-Arch, Vol. 1, 1930, p. 533.

REVIEWS.

Wings Over the World.

"Indicator." W. H. Allen and Co., London, 1943. 6d. net.

This little book has a considerable amount of air transport sense packed into its thirty-six pages. Its sub-title is a realistic approach to our air transport problem.

The first section is entitled "Taking stock of our position" and is a quick survey of the position as it now is and the American position. At the end of the chapter there is quoted, from G. E. R. Sherrington's "A Hundred Years of Inland Transport," "Transport is a social function, its object the improvement of the standard of living of the population. It is the duty of the nation to lead them hand in hand that they may continue to serve to the best of their joint abilities in the common weal." The author finishes the chapter by saying, "Above all we should establish the basic principle that all means of transport must be applied so as to be complementary and not competitive."

That is an ideal to be aimed at, but one not likely to be achieved so long as the profit-making motive dominates. It will require a very carefully thought out organisation to steer the course between a monopoly which ceases to be enterprising and a competitive system which leads to overlapping and waste.

In the second section the author asks what the aeroplane will carry after the war: passengers, goods and mail. He estimates that 2,500 passengers a week will fly in and out of Great Britain, excluding European traffic. The figure is probably on the conservative side, and makes an interesting comparison with Dr. Warner's figures in his 1943 Wilbur Wright Memorial Lecture.

One cannot forbear from quoting the last suggestions of the author with reference to an Airways Corporation. "If I were Air Minister . . . I should appoint to the Board (a) men who had absolutely no interests in sea, rail or road transport, and (b) some men with long and wide experience of overseas and air transport operation."

The functioning of the newly-appointed Board of British Overseas Airways Corporation will be watched by the author and many others in aviation with considerable interest and with no less anxiety.

The Testing of High Speed Internal Combustion Engines.

Arthur W. Judge, A.R.C.Sc., D.I.C.Wh.Sc., A.M.I.A.E., A.F.R.Ae.S. Third Edition. 1943. Chapman and Hall. 42/- net.

The last edition of this well-known work was published in 1932 and in the intervening eleven years there has been a considerable development in engine testing methods and appliances, fuels, etc., which has necessitated the adding of much new matter and the re-writing of some of the old. In Chapter I, on General Principles, for example, details of anti-knock fuels have been added, and more valuable notes on thermal efficiency, volumetric efficiency, etc. In Chapter II, on Test Procedure, there are very considerable additions on recent methods of detecting detonation, and practical effects of detonation and road testing.

Mr. Judge has, indeed, thoroughly revised every chapter and brought it as up to date as possible, although when the censorship comes to an end it may be said he will be called upon for a fourth edition. In particular, however, he has added much on Pyrometers, Instruments and Aircraft Testing Methods and American Test Equipment, and new chapters on Cathode Ray Indicators and Testing of High Speed Compression Ignition Engines.

This third edition of Mr. Judge's book will prove an excellent reference book for all those engaged on engine testing. A word of praise should be given to the publishers for the presentation of the many diagrams and photographs and the clarity of their printing.

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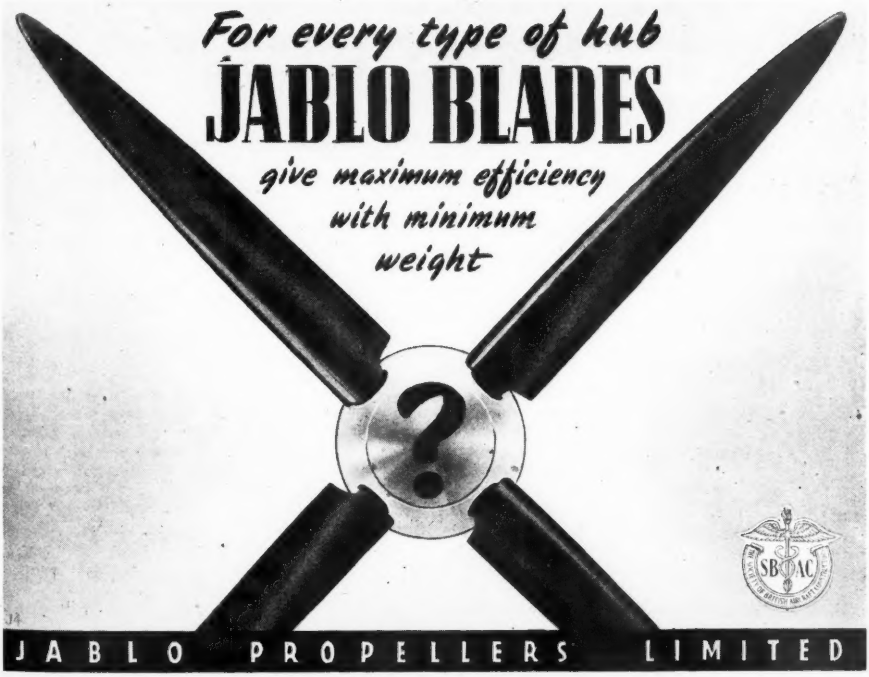
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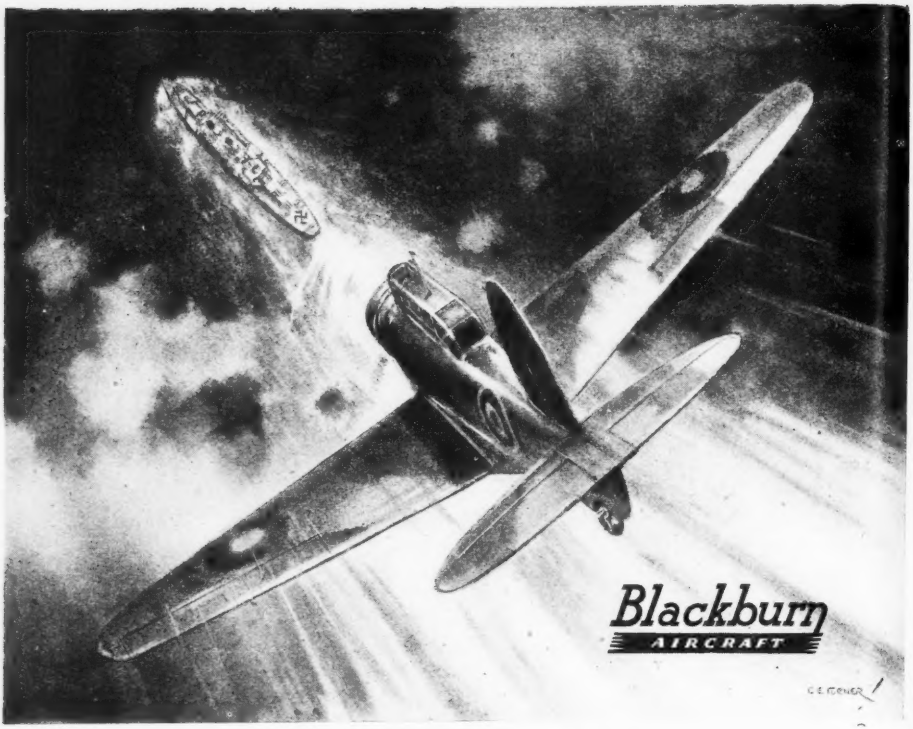

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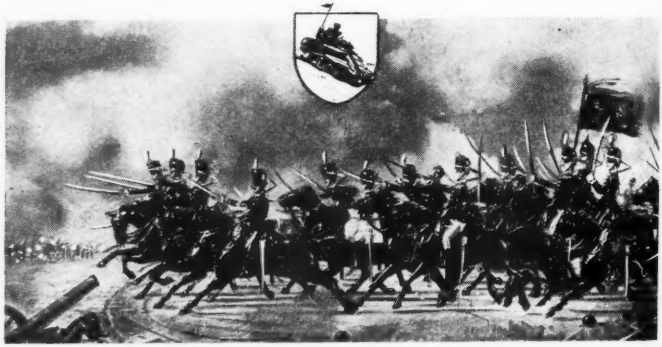

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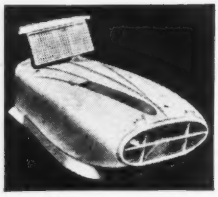

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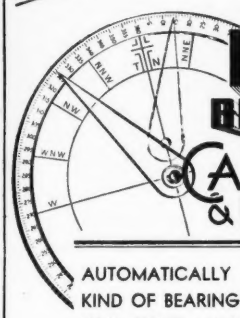

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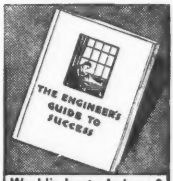

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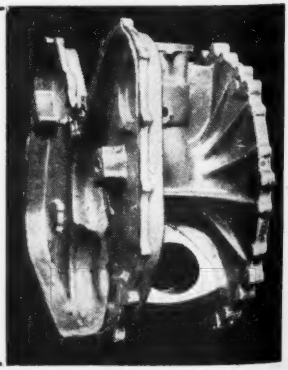

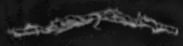

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